Consistent Fusion of Leg Kinematics and Inertial Measurements for State Estimation of Legged Robots

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1 Introduction

The control performance of legged robots and floating base systems in general strongly depends on the underlying state estimation. This becomes especially important as soon as it comes to dynamic maneuvers or challenging terrain, where purely leg kinematics based pose estimators often fail. In order to avoid the usage of an external tracking system, we propose a filtering method that integrates joint sensor measurements with data from an Inertial Measurement Unit (IMU) for a precise postural state estimation. Including the absolute position of the footholds into the filter state enables a simple and consistent representation of the model equations and avoids unnecessary assumptions on the shape of the floor, the type of gait, or even the number of legs.

2 State of the Art

Legged robots distinguish themselves from other robotic platforms trough their intermittent foot-ground interactions. Usually, the current leg configuration can be determined by joint encoder measurements and the known leg kinematics equations. This yields information that can potentially be used for state estimation. However, there exist no off-the-shelf solutions for properly extracting this information. Matching the leg configurations between subsequent timesteps is a common approach for implementing legged odometry [3, 4, 6]. The drawback is, that it requires a minimum of three simultaneous ground contacts and that it is prone to full pose drift. Lin et al. [6] improved this approach by augmenting it with measurements from a mounted IMU in order to handle flight phases on a hexapod robot.

Reinstein and Hoffmann [8] presented a data-driven approach using joint encoders, pressure sensors and a mounted IMU. They searched for significant sensory based indicators in order to determine the stride length when given some specific scenario. By appropriate training, they managed to limit the position drift and to handle slippage of the feet. In contrast to this, model based observers have been implemented as well. Based on a two dimensional dynamic model, Aoustin et al. [1] designed nonlinear observers for estimating the 2D posture of their bipedal robot. Assuming planar spring-mass running, Gur and Saranli [5] proposed a generic, model-based state estimation technique.

Extending the sensor setup on the legged platform with additional exteroceptive sensors has been investigated as well. Chilian et al. [3] implemented a multisensor fusion algorithm merging inertial measurements, legged odometry, and visual odometry. In order to avoid position drift, legged odometry has also been fused with GPS data [4].

3 Contribution

We present an Extended Kalman Filter (EKF) based state estimator which fuses information from the leg kinematics with data from an on-board IMU [2]. We avoid using processed information and directly access the raw sensor data, that is, the angular readings of the joint encoders and the acceleration and rotational rate measurements of the IMU. The key feature of the filter design is the inclusion of the absolute position of all footholds into the filter state, whereby simple and precise model equations can be formulated which accurately capture the uncertainties associated with the intermittent ground contacts. With this, we can avoid assumptions on the shape of the floor or on the employed gait pattern. Except for the unobservable absolute position and yaw angle (i.e., the rotation around the gravity vector), the resulting filter is able to precisely estimate the full pose of the legged robot, including all velocities.

The IMU measurements are used for the prediction step, whereby, using an appropriate stochastic model, the filter states are properly correlated to each other. Foot slippage can be handled by modeling some noise on the predicted foothold position. Subsequently, the leg kinematics measurements are employed to correct the predicted state. They represent relative position measurements between main body and footholds. Based on this information, the EKF is able to simultaneously update the location of the footholds as well as the pose of the main body. In fact, the presented approach can be interpreted as a simultaneous localization and mapping (SLAM) algorithm, whereby the positions of the footholds build up an elevation map of the environment.

The proposed approach was extensively tested in simulation and on a real platform, where the presented filter was used for closing the control loop. Results obtained on a real quadrupedal robot are depicted in Figure 1. Using a virtual model control approach, the robot walks along a square trajectory. Although the absolute position and the yaw angle are not observable, the corresponding estimates exhibit only slight drift when compared with data from an external motion tracker. In a local context the filter yields very precise state estimation. The RMS values of the errors of the estimated inclination angles (roll and pitch) are smaller than 1 deg. For the velocities the RMS values are even below 0.015 m/s. Ignoring the data from three of the feet, the approach has also been validated for single legged platforms, whereas especially the drift on the yaw angle gains in magnitude. A dynamic trotting gait has been evaluated within a simulation environment including realistic noise levels (see Figure 2). The effects of unobservable absolute position and yaw angle can clearly be perceived. The leg kinematics measurements directly correlate the estimate of the main body position and the estimates of the foothold positions and thereby strongly limit the drift.

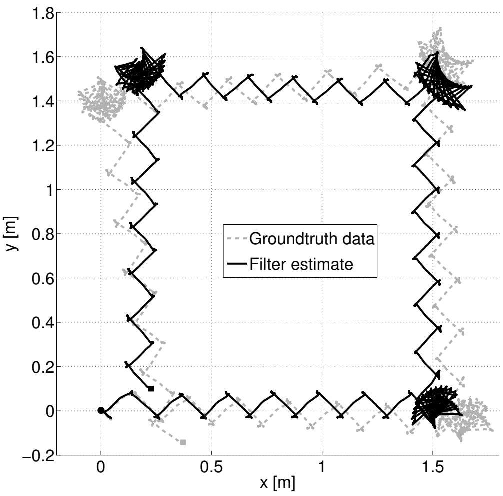

Figure 1: Square trajectory of a real quadruped robot obtained with a virtual model control approach.

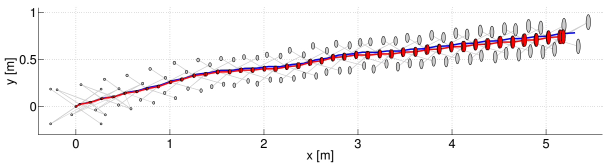

Figure 2: 2D view of a 5 m trotting sequence in simulation. The uncertainties of the main body and foothold locations are represented by the corresponding 1σ-ellipses.

4 Discussion

In the context of legged robotics, state estimation has not been extensively discussed so far. A large part of the ongoing research is still limited to simulation environments and a lot of real platform use external tracking systems. Of course there are also control approaches which do not need a full postural estimate. This often concerns smaller and underactuated systems. As soon as it comes to more sophisticated platforms and control algorithms, e.g. virtual model control or the famous approach of Raibert et al. [7], an estimate of the robot pose becomes indispensable.

From this necessity arises the question what specifications are imposed on the state estimator: which states need to be estimated? what precision is required? what bandwidths need to be attained? Also the presented approach raises a few questions. First the unobservable state need to be handled in some way. Possible approaches include partitioning the filter state or formulating pseudo-measurements. The current filter can also be extended in order to consider further sensor devices. An interesting extension would be to install some range sensor onto the legged platform which could be used for localization as well as for path planning and foothold selection.

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